



Influence of the activator concentration of sodium silicate on the thermal properties of alkali-activated slag pastes



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HIGHLIGHTS

- As concentration of Na₂O increased, up to a certain value, the compressive strength increased.
- Increasing the concentration of Na₂O up to 10.5% did not show further increase in strength.
- Concentration 6.5% of Na₂O showed higher residual strength after firing than 10.5% of Na₂O.
- AAS paste activated with lower concentration of Na₂O showed higher thermal shock resistance.

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ABSTRACT

Ground granulated blast-furnace slag (slag) pastes were chemically activated using sodium silicate with different Na₂O concentrations of 3.5%, 5.5%, 6.5% and 10.5%, by slag weight. The specimens were subjected to elevated temperatures ranging from 200 °C to 1000 °C with an increment of 200 °C for 2 h. Compressive strength before and after firing were measured. Water quenching test was applied to determine thermal shock resistance. The various decomposition phases formed and the morphology of formed hydrates were identified using X-ray diffraction (XRD), thermogravimetric analysis (TGA), derivative thermogravimetric analysis (DTG), scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). The results indicated that compressive strength before or after firing increased with increasing Na₂O concentration up to a certain level, then no extra improvement and deterioration was observed. Higher Na₂O concentration had adverse impact on the thermal shock resistance.

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1. Introduction

Portland cement (PC) industries produced about 3.24 billion tonnes of CO₂ per year [1]. The energy demand associated with PC production is about 1700–1800 MJ/tonne clinker [2], which is the third largest use of energy, after that of aluminium and steel manufacturing industries [3]. Not only CO₂ releases from cement manufacture, but also SO₂ and NO_x which cause the greenhouse effect and acid rain [2]. In addition, PC production consumes considerable amounts of virgin materials, producing each tonne of PC of which about 1.5 tonnes of raw materials is needed [2]. One alternative to reduce cement is using of blended cement. The second alternative is using alkali-activation of slag, fly ash (FA), burned clay and other aluminosilicate materials [4–6]. Today the focus is no longer on obtaining new binders, but on developing materials with sustainably high mechanical strength, fire resistance, higher durability and other characteristics. One option to

improve some special properties of alkali-activated slag (AAS) paste/mortar/concrete is to increase the activator concentration.

The chemical composition of alkali activation as well as the nature and quantity of the activators have a major effect on the AAS system, of which it has been reported that activator type and dosage, curing temperature, specific surface area of slag [7], modulus ratio [8–10] and slag nature [8] are the important parameters in alkali activation process. Krizan and Zivanovic [9] reported that the hydration process of AAS cement was influenced by sodium content and silica modulus. Fernández-Jiménez et al. [7] studied the influence of many factors affecting mechanical strength of AAS mortars. They reported that the nature of activator showed the significant effect on the development of mechanical strength followed by activator concentration, curing condition and slag fineness.

The higher concentration of activator may have a beneficial effect on some properties of AAS system, of which Al-Otaibi [11] reported that the choice of the type of activator and dosage is very important in AAS concrete; with the higher dosage resulting in higher strength. Neto et al. [12] activated slag mortars with sodium

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silicate at concentrations of 2.5%, 3.5% and 4.5% of Na₂O, by weight. They reported that an increase in activator amount caused an increase in the degree of hydration, which led to an increase in CSH volume and accordingly, a reduction in porosity. Allahverdi et al. [13] activated slag pastes with alkaline activator at concentrations ranging from 1% to 6% of Na₂O, by weight. They found an increase in the workability and compressive strength with increasing Na₂O concentration. Wang et al. [14] used 0.5%, 1% and 1.5% concentrations of 5 M alkaline solutions to activate slag paste mixtures. They found higher workability and compressive strength with increasing activator concentration. Chi [15] activated slag concretes with liquid sodium silicate at concentrations of 4%, 5% and 6% of Na₂O, by weight. The results showed an increase in the compressive strength and splitting tensile strength with increasing activator concentration. Acevedo-Martinez et al. [16] reported that the compressive strength of AAS mortars activated with waterglass at different concentrations of 4%, 6% and 10% of Na₂O increased with increasing Na₂O concentration.

Chi [15] studied the effect of different concentrations of 4%, 5% and 6% of Na₂O, by weight, on the mechanical properties and durability of AAS concretes. The results showed an increase in the mechanical strength and durability with increasing Na₂O concentration. Yang et al. [17] reported that the higher the Na₂O to source material ratio, the better the compressive strength development at long term age. Yang et al. [18] reported that the higher the Na₂O to source material ratio (from 0.038 to 0.089), the higher the compressive strength. Atiş et al. [10] used different activator types at different Na₂O concentrations of 4%, 6% and 8%, by weight, to activate AAS mortars. They reported that increasing the sodium concentration showed an increase in the compressive and flexural strength. Bougara et al. [19] activated mortars with different concentrations of KOH (2 M, 3 M and 4 M). They reported that increasing KOH concentration from 2 M to 3 M caused an increase in strength, but no increase beyond this level (3 M). Rashad et al. [20,21] found higher compressive strength with higher concentration of Na₂SO₄ activated slag pastes. Escalante-Garcia et al. [22] used sodium silicate with modulus of 1.7 to activate slag in AAS concretes containing different slag contents. The concentrations of Na₂O were 4%, 6% and 8%, by weight. The results showed higher compressive strength with higher Na₂O concentration. Cincotto et al. [23] reported that the porosity decreased with increasing Na₂O concentration. Bilim et al. [24] found an increase in carbonation depth of AAS mortar specimens with lower concentration of sodium silicate. The higher concentration of activator decreased the carbonation depth of the specimens. On the other hand, increasing Na₂O concentration may cause some defects on some properties of AAS system, of which Krizan and Zivanovic [9] reported that drying shrinkage of AAS binders increased with increasing dosage of waterglass. Cincotto et al. [23] activated slag mortars with sodium silicate at concentrations of 2.5%, 3.5% and 4.5% of Na₂O. They reported that autogenous shrinkage increased with increasing Na₂O concentration. Atiş et al. [10] prepared activated mortars with different Na₂O concentrations of 4%, 6% and 8%, by weight. They found an increase in the drying shrinkage with increasing Na₂O concentration. Allahverdi et al. [13] prepared pastes with different Na₂O concentrations of 1%, 2% and 3%, by weight. They found higher drying and autogenous shrinkage with higher Na₂O concentration.

AAS is one of the prospective materials in the field of fire protection because it exhibits remarkable high-temperature resistance and very favorable mechanical properties. Therefore, this type of materials is capable of replacing traditional PC or blended cement as binder where high temperature resistance of the material is required. Rashad et al. [21] studied the effect of elevated temperatures on slag pastes activated with Na₂SO₄. They compared the relative strength of activated slag with that of PC. They reported that the relative strength of activated slag pastes, up to 600 °C, was

Table 1
Chemical composition of slag.

Oxide composition	Slag (%)
SiO ₂	36.95
Al ₂ O ₃	10.01
Fe ₂ O ₃	1.48
CaO	33.07
MgO	6.43
Na ₂ O	1.39
K ₂ O	0.74
SO ₃	3.52
TiO ₂	0.52
P ₂ O ₅	0.1
MnO ₂	0.52
Cl ⁻	0.05
L.O.I.	0

higher than that of PC. Guerrieri et al. [25] studied the effect of elevated temperatures, up to 1200 °C, on the residual compressive strength of AAS concrete activated with dry powder sodium metasilicate and hydrated lime. The results indicated that approximately 76% remaining strength at 200 °C. After exposure to 400, 600 and 800 °C, the remaining strength was 73%, 46% and 10%, respectively. Guerrieri et al. [26] studied the residual strength properties of AAS pastes exposed to elevated temperatures. Dry powder sodium metasilicate with silicate modulus (SiO₂/Na₂O) (Ms ~ 1.0) and dry hydrated lime were used as activators. The results indicated that AAS pastes exhibited a rapid strength loss of approximately 60% between 100 °C and 200 °C, a further strength loss in the order of 30% at 800 °C and total loss of strength occurred at 1200 °C.

The review of the literature has clearly indicated that there are few publications related to the performance of AAS system under the effect of elevated temperatures. In particular, until now, there has not been any publication studied the behavior of AAS pastes activated with different concentrations of sodium silicate under the effect of elevated temperatures ranging from 200 °C to 1000 °C with an increment of 200 °C for 2 h. Along with this, there has not been any publication studied the behavior of rapid temperature changes on AAS pastes activated with different concentrations of sodium silicate. Therefore, this investigation experimentally studied these items. Moreover, this study aims to respond to four extra issues named lower emission of pollutants into atmosphere, reduction in consumption of natural resources, reduction in the fuel and eliminate slag disposal. Thus, this investigation will therefore add valuable knowledge to the AAS system.

2. Experimental details

2.1. Materials

The source raw material used in the current study was water quenched slag that was delivered from disposal waste resulting from Helwan steel factory (in Cairo-Egypt). The slag was then finely ground in a laboratory ball mill to reach a surface area of 300 m²/kg. Its specific gravity was 2.9. The chemical composition is given in Table 1. The diffractograms of raw slag sample is shown in Fig. 1. The wide diffusive amorphous hump is between 25° and 35° (Fig. 1) indicates that the slag is mostly amorphous. A commercial liquid sodium silicate which had silica modulus (SiO₂/Na₂O) of 1.7 with concentrations of 3.5%, 5.5%, 6.5% and 10.5% of Na₂O, by slag weight, was used as alkali activator.

2.2. Mixture proportions

Four AAS paste mixtures were prepared. The pastes were activated with sodium silicate. They formulated with four different concentrations of Na₂O estimated as 3.5%, 5.5%, 6.5% and 10.5%, by slag weight. The mixtures were designated as N3.5, N5.5, N6.5 and N10.5, respectively. Mixture proportions are detailed in Table 2. All pastes were prepared using the standard water of consistency.

2.3. Methods

The solution of sodium silicate dissolved in mixing water was prepared. Source slag was added to the sodium silicate solution which has been previously placed in the bowl of a Hobart planetary mixer and mixed for 5 min period followed by 2 min resting and

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